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Effectiveness of mechanical thinning and prescribed burning on fire behavior in *Pinus nigra* forests in NE Spain

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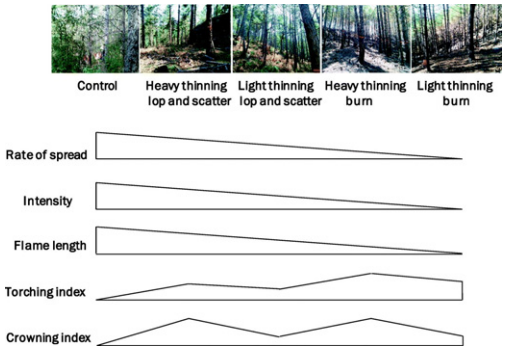
HIGHLIGHTS

- The influence of thinning intensity and the type of slash management on forest fire behavior
- All treatments studied reduce fire intensity and increase the resistance of *Pinus nigra* forests
- Thinning followed by fire is the most effective treatment for reducing crown fire potential
- Crown fire potential is higher for light thinning, but only with very extreme climatic conditions
- Treatments provide better fire suppression opportunities and higher probabilities of tree survival

GRAPHICAL ABSTRACT



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ABSTRACT

Fuel treatments can mitigate present and future impacts of climate change by reducing fire intensity and severity. In recent years, *Pinus nigra* forests in the Mediterranean basin have been dramatically affected by the new risk of highly intense and extreme fires and its distribution area has been reduced. New tools are necessary for assessing the management of these forests so they can adapt to the challenges to come. Our main goal was to evaluate the effects of different fuel treatments on Mediterranean *Pinus nigra* forests. We assessed the forest response, in terms of forest structure and fire behavior, to different intensities of low thinning treatments followed by different slash prescriptions (resulting in: light thinning and lop and scatter; light thinning and burn; heavy thinning and lop and scatter; heavy thinning and burn; and, untreated control). Treatments that used fire to decrease the resulting slash were the most effective for reducing active crown fires decreasing the rate of spread and flame length more than 89%. Low thinning had an effect on torching potential, but there was no difference between intensities of thinning. Only an outcoming crown fire could spread actively if it was sustained by a high-enough constant wind speed and enough surface fuel load. Overall, treatments reduce fire intensity and treated areas have a more homogenous fire behavior response than untreated areas. This provides opportunities to extinguish the fire and reduce the probability of trees dying from the fire. It would be helpful to include ecological principles and fire behavior criteria in silvicultural treatment guidelines in order to perform more efficient management techniques in the future.

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1. Introduction

Forest managers can apply different possible fuel treatments, such as thinning, pruning or removal of surface fuels, using mechanical tools or

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prescribed fire, to mitigate the potential wildfire severity, modify stand structure and restore forest functions (Fulé et al., 2001b; Agee and Skinner, 2005). It is known that altering fuel loads and fuel continuity through silvicultural treatments decreases the treated area's vulnerability to crown fires (Johnson et al., 2007; Fernandes and Rigolot, 2007).

Crown fires pose the greatest threat to fire control (Albini and Stocks, 1986) as they often spread rapidly (Wade and Ward, 1973) and burn with greater intensity than surface fires (Rothermel, 1983). They are divided into three categories: a) passive crown fires (individual or small groups of trees torch out but flame is not maintained in the canopy); b) active crown fires (surface and canopy fuel stratum burn and crown fire spread depends on the heat released by the surface fuel layers); and c) independent crown fires (fire spreads in the canopy independently of the heat released from the surface fire), which only occur rarely and under extreme conditions (van Wagner, 1993). Traditional direct attacks are impossible for these types of fires (mainly active and independent crown fires) because the fire behavior characteristics are extreme, i.e. high heat intensity, long spotting distances and large flame lengths and rates of spread (Scott and Reinhardt, 2001). Therefore, knowledge about the effectiveness of treatments and the post-treatment forest stand characteristics under which crown fires hardly ever initiate and propagate are of primary concern.

The effectiveness of different treatments, mainly prescribed burning, in reducing the fire hazard has been largely demonstrated in experimental fires and wildfire case studies using simulation models, mostly for dry conifers of western USA (Carey and Schumann, 2003; Graham et al., 2004; Peterson et al., 2005). However, few studies have evaluated the effectiveness of fuel treatments at the stand level in Mediterranean species (i.e. Duguy et al., 2007; De las Heras et al., 2004; Casals et al., 2016), or have compared the effectiveness of different treatments that combine mechanical treatments and prescribed fires in this region.

In the NE Iberian Peninsula (Catalonia, Spain) *Pinus nigra* forests cover >130,000 ha (Piqué et al., 2014) between pure and mixed forests, and are distributed mainly in the Pre-Pyrenees and in some points in the southern and coast ranges. *Pinus nigra* forests have high economic and social importance in NE Spain as they contribute greatly to the wood market of the area. Historically, these forests were open stands with a surface fire regime maintained by pastures (Tapias et al., 2004; Fulé et al., 2008). Since the beginning of the 20th century, traditional management activities, such as selective felling for producing poles, has generated closed stands and increased understory vegetation growth.

The recent decrease in forest practices due to rural abandonment and the increase in high intensity wildfires have led to a notable regression of surface and the quality of *Pinus nigra* forests, which are particularly vulnerable to climate change and classified as a Priority Natural Habitat for Conservation by the Habitats Directive. *Pinus nigra* is well-adapted to low intensity fires with a thick scorch and self-pruning strategy (Fulé et al., 2008). However, nowadays these forests have structures with high vertical continuity and significant fuel accumulation, which makes them highly vulnerable to high intensity forest fires.

As severe wildfires in recent years have damaged *Pinus nigra* forests in particular (Pausas et al., 2008), fire managers have become more concerned about the effectiveness of current fuel treatment practices (e.g. thinning, prescribed burning or a combination of both) to reduce fire risk and severity. Fuel treatments modify species composition, structure, availability, distribution, fuel moisture and surface-wind behavior (Graham et al., 1999). The aim of these treatments is generally to reduce the fuel load so that, if a wildfire takes place, it will spread more slowly and with less intensity, and be less severe and easier to control. To achieve this aim while ensuring that forests are resilient against wildfires, fuel treatments should consider one or more of the following four basic principles (Agee and Skinner, 2005): reduce surface fuel, increase the height to the live crown, decrease crown density and keep large trees of resistant species.

The approach most widely used to evaluate the effectiveness of fuel treatments is simulation tools for predicting fire behavior and comparing the success of hazard reduction techniques (Fulé et al., 2001b, 2002; Manson et al., 2007; Kobziar et al., 2009). From the description of the vegetation and the knowledge of certain environmental and topographic factors, simulation tools make it possible to predict fire behavior descriptors (rate of spread, intensity, heat released, flame length and type of fire, among others). Within the wide range of forest fire simulation tools currently available, those based on the Rothermel (1972) fire spread model are the most widely used for assessing the effectiveness of silvicultural treatments (Fernandes, 2009).

The objective of this study was to evaluate the effect on forest structure and fire behavior of two intensities of mechanical thinning combined with two slash prescriptions in *Pinus nigra* forests in NE Spain, also considering different fire weather scenarios. The treatments studied were two intensities of low thinning (light and heavy) combined with two slash management techniques (prescribed burn or lop and scatter) because these are the most widely discussed in the area. We hypothesized that (1) heavy intensity thinning compared to light intensity thinning would increase the surface fuel load more but decrease the distance between the surface and the crown; (2) slash burn would decrease the amount of dead fine fuel on the surface and increase the distance between the surface and crown fuel while scatter and lop would increase dead surface material. In this study, we present the preliminary results from one site before and immediately after the treatments. The study belongs to a wider long-term experimental experience with other sites sampled at different times after treatment and aims to provide guidelines for forest managers to help them choose the most suitable treatment for reducing forest fire risk.

2. Material and methods

2.1. Study site

The study area (3.9 ha) is located in the Pre-Pyrenean range, Catalonia, NE Spain, at 1.46° E and 41.95° N. The forests in the area are generally composed by pure Spanish black pine (*Pinus nigra* ssp. *salzamanni*) stands with a *Buxus sempervirens* understory, and are intensely managed for wood and firewood production. Soil conditions are determined by underlying sedimentary detritic rocks, mainly lutites with centimetric interbedded sandstones and limestones, with a thickness ranging from 10 to 40 cm.

The study area is characterized by a Mediterranean climate, with cold winters and warm springs and summers. Monthly mean temperatures range from 4 °C in January to 22 °C in August. Annual precipitation is around 550 mm and mostly occurs in autumn and spring, with occasional storms in summer. During the fire season the area is mainly affected by westerly winds with a 9 km h^{-1} speed on average and gusts up to 37 km h^{-1}.

2.2. Treatments

Within the study area four different mechanical treatments were performed, together with a control unit. Stands had similar slope (35%) and elevation (850 m). Treatments were divided into thinning intensity and type of slash management for comparison. The resulting 5 treatment units were: light thinning and lop and scatter (TL), light thinning and burn (TLB), heavy thinning and lop and scatter (TH), heavy thinning and burn (THB) and untreated control (C).

Mechanical treatments consisted of low thinning of two intensities, light thinning (final canopy cover ≥ 75%) and heavy thinning (final canopy cover 50–60%). For heavy intensity thinning, full trees selected for removal were lopped and trunks removed from the site. Both treatments cleaned the undergrowth vegetation higher than 1.3 m. Slash with a dimeter larger than 5 cm was cut up to 1 m long and left on the ground. Prescribed burning was carried out by the Forest Actions Support Group (GRAF) of the Autonomous Government of Catalonia

(Generalitat de Catalunya). Thinning, and then burning, were completed in April–May 2015.

During the prescribed burning the temperature was between 19 °C and 23 °C and the relative humidity was 41–50%. To monitor the burning conditions, fire residence time (minutes) above 60 °C and 120 °C and maximum temperature at the base of the trunk were measured in 18 trees per treatment with K-thermocouples (4 mm) connected to dataloggers (Testo 175), packed with a fireproof blanket and buried in the soil (Table 1).

2.3. Sampling methods

Within the study site different sampling methods were used to monitor the vegetation response to treatments. Data were collected before and immediately after treatments.

Three 10-m circular radius plots per treatment were established for overstory and understory sampling. Diameter at breast height (DBH), total height (TH), height to live crown base (CBH) and crown width (CD) were recorded for all trees with a DBH ≥7.5 cm. Forest cover was also recorded with hemispherical canopy photographs. Two understory 10 × 0.5 m transects for each plot were placed next to the center of the plot and herbaceous, shrub and slash cover and maximum height were recorded for each 0.5 × 0.5 m square. The total mean height was calculated as the mean of the maximum heights weighted by cover values.

Crown biomass was estimated with allometric equations for foliage (Koukoulomatis and Mitsopoulos, 2007). Then the available canopy bulk density was defined as the mass of available canopy fuels per unit of canopy volume.

Fuel load estimations were made for all treatments. Specifically, litter and understory loading were measured by destructive sampling of five 1 m × 1 m frames (Sikkink and Keane, 2008). Fuel was classified according to vegetation type (litter, herbaceous, slash and shrubs) and as dead fuel (by time-lag size class: 1 h, ≤ 0.64 cm; 10 h, 0.64–2.54 cm; 100 h, 2.55–7.62 cm) or live fuel (woody or herbaceous). To determine fuel load on a dry weight basis, some representative samples of all fuel classes were oven-dried in the laboratory (at 80 °C for 48 h).

2.4. Fire severity

Two years after the treatments, we measured tree mortality and diameter of dead trees in each treatment (a tree was considered alive when green foliage was present in the crown, otherwise it was considered dead). Crown base height (CBH) was also measured immediately after the treatment and 2 years after the treatment, and the percentage of crown length reduction between immediately after and 2 years after the treatment (Crown length = Total height of tree − CBH) was estimated.

Stem injury was characterized by maximum bole scorch height (BSH). In addition, the diameter growth two years after the treatments of five dominant trees per plot was measured with DB20 dendrometers.

2.5. Fire behavior modelling in different fire weather scenarios

NEXUS (ver.2.0, Scott, 1999), a stand level fire behavior model, was used to observe differences in fire behavior between treatments. NEXUS uses existing models of surface and fire behavior to simulate overall fire spread and intensity (Scott and Reinhardt, 2001).

Observed fuel loads were used to create custom fuel models. Fine woody fuel load was obtained using equations from Casals et al. (2016). Fuel bed depth was calculated from understory transect samples. Surface area to volume ratios and dead and live heat content were estimated based on Cohen et al. (2003).

Fire weather scenarios representing the 50th, 75th and 99th percentiles of temperature, relative humidity and wind speed were calculated with 16 years of data from a meteorological station located 10 km from the study area (Table 2). Weather values were calculated according to the conditions of the summer months (July–August) with a west wind, which are the conditions that cause fires in the area (Piqué et al., 2011). The wind reduction factor was chosen following the reference guide for NEXUS 2.0.

From the weather percentiles, 1 h, 10 h and 100 h fuel moisture content were calculated according to the tables in Rothermel (1983). Live woody fuel moisture was estimated from data provided by the Department of Agriculture of the Autonomous Government of Catalonia (Generalitat de Catalunya).

Type of fire (surface fire, passive crown fire or active crown fire), rate of spread (m min^{-1}), heat/area (kJ m^{-2}), fireline intensity (kW m^{-1}), flame length (m), torching index (km h^{-1}, open wind speed needed to initiate crown fire) and crowning index (km h^{-1}, open wind speed needed to keep an active crown fire) were recorded for 50th, 75th and 99th percentile weather scenarios. Slope was fixed at 35% (mean value for the area), in order not to confuse the response to treatment.

3. Results

3.1. Forest structure and fuel characteristics

Total fuel loading was 40 t ha^{-1} prior to treatments and between 23 t ha^{-1} (light thin/burn) and 72 t ha^{-1} (heavy thin/lop and scatter) following treatments (Table 3). Without treatment, dead and live fuel percentages were similar (58% and 42% respectively) whereas after treatments almost all the fuel was dead (98% or more). Lopped and scattered slash resulted in higher dead fuel loads (55–72 t ha^{-1}) than treatments followed by fire (23–34 t ha^{-1}) or in the control (23 t ha^{-1}). The total amount of fuel was reduced in burn units compared with lop and scatter, especially 1 h and 10 h fuel, while 100 h fuel was similar to non-burned units due to an increase in slash resulting from thinning and low consumption of thicker diameters in the prescribed burns (Fig. 1).

Light thinning, but mainly heavy thinning, with lopped and scattered slash, increased the total amount of fuel compared with no treatment. Thinning created a lot of dead slash, especially 1 h fuel load (from 18 t ha^{-1} in C to 28 t ha^{-1} in TL and 32 t ha^{-1} in TH). All the fuel that before the thinning treatment was part of the living woody fuel (42%) almost completely disappeared (between 0 and 5%) after the treatment, as it was converted into dead fuel. Heavily thinned units contained a considerable amount of 100 h fuel load (35 t ha^{-1}), including remains from the crown that were incorporated as surface dead fuel.

Fuel bed depth decreased considerably with treatments (Table 3). The control unit contained tall shrubs and had a higher fuel bed depth

Table 1
Characteristics of prescribed burns in the experimental units. TLB, Light thinning and burn; THB, Heavy thinning and burn.

Treatment	Maximum temperature (°C)		Residence time (minutes)			
			T > 60 °C		T > 120 °C	
	Mean	Range	Mean	Maximum	Mean	Maximum
TLB	481	20–871	79.5	271.7	37.8	240.7
THB	448	36–676	99.0	494.5	60.5	263.0

Temperatures were measured on the ground. Residence time corresponds to minutes with temperatures above 60 °C or 120 °C respectively.

Table 2
Weather and fuel moisture conditions for the modelled potential fire behavior.

Variable	50th percentile	75th percentile	99th percentile
1 h fuel moisture (%)	7	6	5
10 h fuel moisture (%)	8	7	6
100 h fuel moisture (%)	9	8	7
Live woody fuel moisture (%)	110	98	72
Wind speed (km h^{-1})	7.5	9.1	14.1
Temperature (°C)	29.5	32.0	38.0

Table 3
Surface fuel characteristics in control and treated stands (mean ± se). C, Control; TL, Light thinning and lop and scatter; TLB, Light thinning and burn; TH, Heavy thinning and lop and scatter; THB, Heavy thinning and burn. WT, Total fuel load; W1 h, 1 h fuel load (<6 mm); W10 h, 10 h fuel load (6–25 mm); W100 h, 100 h fuel load (25–76 mm).

Treatment	WT	W1 h	W10 h	W100 h	Live herbaceous fuel load	Live shrub fuel load	Fuel bed depth
	(t ha^{-1})	(t ha^{-1})	(t ha^{-1})	(t ha^{-1})	(t ha^{-1})	(t ha^{-1})	(cm)
C	40.41 ± 4.95	17.64 ± 1.97	3.25 ± 0.43	2.52 ± 0.81	0.02 ± 0.01	16.98 ± 2.83	152.90 ± 19.16
TL	56.68 ± 4.76	28.06 ± 3.62	14.79 ± 0.29	12.43 ± 3.14	0.00 ± 0.00	1.39 ± 0.38	35.50 ± 15.77
TLB	22.95 ± 0.60	8.86 ± 1.36	2.39 ± 0.70	11.71 ± 0.61	0.00 ± 0.00	0.00 ± 0.00	15.00 ± 1.63
TH	72.41 ± 12.79	32.46 ± 6.43	10.73 ± 1.23	28.51 ± 20.33	0.04 ± 0.04	0.67 ± 0.40	42.00 ± 8.84
THB	34.12 ± 14.50	10.41 ± 0.99	1.5 ± 0.08	22.19 ± 13.60	0.00 ± 0.00	0.00 ± 0.00	20.00 ± 2.14

(1.53 m) than the treated units (from 0.35 to 0.45 m in thin/lop and scatter units and from 0.14 to 0.20 m in thin/burn units), in which shrubs were knocked down by the treatment.

Heavy thinning had a greater impact on the forest stand characteristics than light intensity thinning (Table 4). Tree density, canopy cover and basal area decreased due to heavy treatment. The forest structure was similar in the control unit and light thinning. Slash disposal did not alter the forest stand characteristics in heavy or light thinning treatments.

3.2. Potential fire behavior

For these results the mean site slope value used was 35%. Nexus is highly sensitive to CBH; therefore, for simulation purposes, the value

Control
Light thinning and lop and scatter
Light thinning and burn
Heavy thinning and lop and scatter
Heavy thinning and burn

Fig. 1. Photographs showing the results of the treatments.

Table 4
Overstory characteristics in control and treated stands. C, Control; TL, Light thinning and lop and scatter; TLB, Light thinning and burn; TH, Heavy thinning and lop and scatter; THB, Heavy thinning and burn.

Treatment	Surface	Tree density	Canopy cover	Diameter	Basal area	Basal area reduction	Available crown bulk density	Crown base height
	(ha)	(trees ha^{-1})	(%)	(cm)	(m^2 ha^{-1})	(%)	(kg m^{-3})	(m)
C	1.21	1592	80	17,8	40	0	0.23	6.9
TL	0.67	1411	80	17,5	34	15	0.19	7.0
TLB	1.05	1411	80	17,5	34	15	0.20	7.0
TH	0.54	690	60	20,6	23	43	0.09	7.9
THB	0.51	690	60	20,6	23	43	0.09	7.6

was fixed as the mean of each treatment, light thinning (7.0 m) and heavy thinning (7.8 m).

Under modeled conditions, the control unit was susceptible to relatively intense fire behavior: fire rate of spread 8–10 m min^{-1}, heat released 46,000–50,000 kJ m^{-2} and flame lengths 8–10 m (Tables 5 and 6). After treatment, fires were less intense: fire rate of spread 1–3 m min^{-1}, heat released 6000–21,000 kJ m^{-2} and flame lengths 1–2 m.

Thinning intensity did not affect the surface fire behavior much (rate of spread, heat released, intensity or flame length), as light and heavy thinning reduced fuel bed depth and increased dead fuel loads. Thinning with slash burn resulted in shorter flame lengths and slower rates of spread compared to thinning followed by lopped and scattered slash.

Modeled fire type was passive for the control unit and surface for the other fuel treatment combinations. Crown fire potential was higher for light thinning than it was for heavy thinning. Compared to heavy thinning, fires in light thinning treatments required slower wind speeds to reach crowns (72–91 km h^{-1} light thin and 80–101 km h^{-1} heavy thin in lop and scatter slash), though all wind speed values were high and unusual for the area (Fig. 2). Treatments followed by fire had no torching potential (the required winds were higher than 337 km h^{-1}).

The wind speeds needed for keeping an active crown fire ranged between 21 and 50 km h^{-1}. Control and light thinning showed similar and slower wind speeds for active crown fire than heavy thinning. The crown fire potential did not change with the slash management type. Under modeled conditions and after treatments, the torching potential was very low and the resulting fire was a surface fire. Only the control unit could have an active fire with wind speeds above 21 km h^{-1}.

When fire behavior in a wide range of weather conditions was compared, the modeled fire behavior was wider and with a higher rate of spread and heat/area for the control unit (Fig. 3). While thin/lop and scatter units, and then thin/burn, had a narrower range of fire behavior possibilities and lower rates of spread and heat released.

3.3. Fire severity and growth response

Mortality two years after the fire was greater in light thinning (414 trees ha^{-1}) than heavy thinning (223 trees ha^{-1}) (Table 7). Light intensity thinning slightly reduced tree density and left many small-diameter trees, which were the most affected by the prescribed burns (the diameter of dead trees was 10 cm). Mortality caused by fire had a greater effect on small-diameter trees and reduced tree density after the fire from 1411 trees ha^{-1} to 977 trees ha^{-1}, which is still higher than in the heavy thinning treatment.

CBH two years after treatments increased basically in the heavy thin/burn units (6%), which in turn reduced crown length (7%). Surface dead fuel load was higher in heavy thinning units, where prescribed burns produced higher intensities and damage to crowns than in other treatments. The reduction in canopy length and bole scorch height was also larger due to this effect.

A positive effect on diameter growth was observed in both the heavy thinning units (lop and scatter or burn), doubling the control and light thinning values (Table 7). Heavy intensity thinning had a greater effect on the growth in diameter of the remaining trees than light thinning and prescribed burns did not influence the growth of dominant trees.

4. Discussion

4.1. Forest structure

Low thinning followed by lop and scatter increased the amount of fine dead fuel (1 h and 10 h load), while low thinning followed by burns decreased the fine dead fuel compared to the control. These results are consistent with other studies where mechanical treatments increase surface fuels but post-treatment burning reduces it (Agee and Skinner, 2005; Stephens and Moghaddas, 2005; Schmidt et al., 2008). Although treatments followed by burns considerably decreased the 1 h and 10 h fuel load, the amount of 100 h fuel load increased approximately 10 t ha^{-1} for light intensity thinning and at least 20 t ha^{-1} for heavy intensity thinning, which suggests that burns were not intense enough to consume the large dead woody vegetation created by the thinning treatments.

Heavy thinning reduced tree density, canopy cover and canopy bulk density and increased crown base height as other studies also point out (Pollet and Omi, 2002, Stephens and Moghaddas, 2005; Vaillant et al., 2009). These changes in stand characteristics correlate to reductions in both ladder and canopy fuels. Light thinning had a less obvious effect on stand characteristics, slightly increasing crown base height and decreasing crown bulk density. However, the distance between the surface fuel and crown layers increased in both intensities of thinning (light and heavy) due to decreases in fuel bed depth as a result of surface fuel clearing.

Table 5
Effects of treatment on potential fire behavior under the 75th-percentile fire weather scenario with a 35% slope. C, Control; TL, Light thinning and lop and scatter; TLB, Light thinning and burn; TH, Heavy thinning and lop and scatter; THB, Heavy thinning and burn.

Treatment	Type of fire	Spread rate	Heat per unit area	Fireline intensity	Flame length
		(m min^{-1})	(kJ m^{-2})	(kW m^{-1})	(m)
C	Passive crown	7.54	45,857	5741	7.53
TL	Surface	2.44	19,653	797	1.68
TLB	Surface	0.80	6290	83	0.61
TH	Surface	2.48	19,960	824	1.71
THB	Surface	0.83	6710	93	0.61

Table 6
Effects of treatment on potential fire behavior under the 99th-percentile fire weather scenario with a 35% slope. C, Control; TL, Light thinning and lop and scatter; TLB, Light thinning and burn; TH, Heavy thinning and lop and scatter; THB, Heavy thinning and burn.

Treatment	Type of fire	Spread rate	Heat per unit area	Fireline intensity	Flame Length
		(m min^{-1})	(kJ m^{-2})	(kW m^{-1})	(m)
C	Passive crown	9.58	49,763	7917	10.03
TL	Surface	2.73	20,698	938	1.80
TLB	Surface	0.90	6631	100	0.64
TH	Surface	2.77	21,038	969	1.83
THB	Surface	0.93	7062	110	0.67

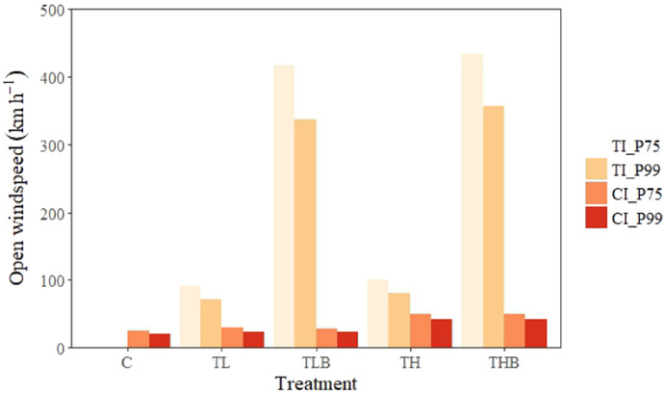

Fig. 2. Torching (TI) and Crowning (CI) indices for different weather scenarios (75th and 99th-percentile) and treatments. C, Control; TL, Light thinning and lop and scatter; TLB, Light thinning and burn; TH, Heavy thinning and lop and scatter; THB, Heavy thinning and burn.

4.2. Potential fire behavior

At the stand level, the effectiveness of fuel treatments depends on the species and its response to the treatment, the intensity of the treatment, the management of the resulting slash and the longevity of the treatment. Simulation tools are useful for evaluating and comparing fuel treatments but they also have several limitations. Simulation results are highly dependent on fuel (surface, ladder and canopy) and meteorological scenario inputs; nonetheless, fuel heterogeneity and variable local environmental conditions make it difficult to accurately describe these parameters (Cruz and Alexander, 2010). We used custom fuel models to obtain a more detailed fuel description. Although it is a more expensive and time-consuming method, it has a lower level of uncertainty compared with other sampling procedures (Keane, 2015). In addition, to characterize the local environmental conditions of the study area, we concentrated on the main weather variables that drive the fires in the area, which allowed us to identify the weather scenarios that could lead to fires.

The relationship between fuel load and fuel bed depth greatly influences fire behavior, particularly the rate of spread. Increasing 1 h load generally increases the rate of spread until the fuel model becomes too tightly packed, then the rate of spread decreases (Burgan and Rothermel, 1984). In our study, treatments followed by lop and scatter increased 1 h load but also decreased the fuel bed depth, which in turn increased the bulk density of the surface fuel, thus reducing the rate of spread.

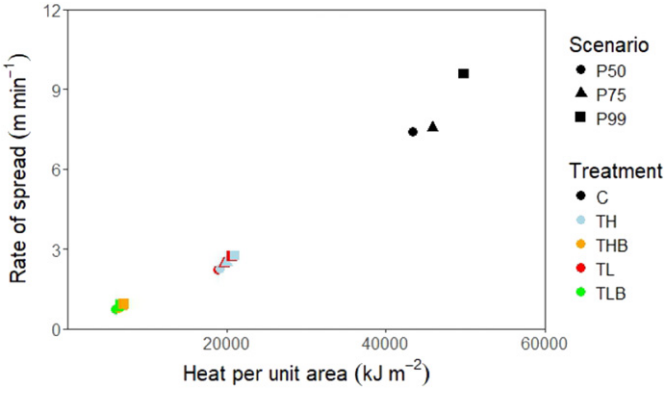

Fig. 3. Heat/area versus Rate of spread for different weather scenarios and treatments. Control; TL, Light thinning and lop and scatter; TLB, Light thinning and burn; TH, Heavy thinning and lop and scatter; THB, Heavy thinning and burn. P50, 50th percentile; P75 Percentile 75th percentile; P99, 99th percentile.

Treatments reduced the high potential of crown fire compared with the control units, which could be expected to torch even in a no-wind situation. Treatments had high torching index (TI) values, which indicates a very low potential for initiating a crown fire. However, crowning index (CI) values were lower than TI values, especially in lightly thinned stands. Some authors have found that when TI and CI values are higher than 42 km h^{-1} the fire hazard is very low (Skog et al., 2006; Huggett et al., 2008). When TI values exceed CI a conditional type of crown fire can occur (Scott and Reinhardt, 2001). In this situation, only an oncoming crown fire is possible with enough constant wind speed and enough surface fuel load to sustain it. This means that in extreme weather conditions, although all treated units could start crowning with winds between 20 and 40 km h^{-1}, they do not have enough capacity for torching. Only low thinning followed by lop and scatter with unusually extreme meteorological conditions (constant wind speed above 72 km h^{-1}) could really maintain an active crown fire.

All fuel treatments influenced the potential fire behavior. However, treatments followed by fire were the most effective in terms of reducing the rate of spread, flame length and intensity. Treatments without fire were efficient enough to reduce the potential fire behavior. The intensity of the treatment did not produce considerable changes in fire behavior. Predicted fires can be classified into different fire suppression levels (based on Rothermel, 1983). Fire behavior in the control unit with high fireline intensities (above 5000 kW m^{-1}) and flame lengths (above 7 m) is likely to produce crowning, spotting and extreme fire behavior. Low thinning followed by lop and scatter reduces both intensity (between 700 and 1000 kW m^{-1}) and flame length (between 1.5 and 2 m) and results in fires that can be extinguished with indirect and parallel attacks. Treatments followed by fire would only allow wildfires with low fireline intensities (below 345 kW m^{-1}) and flame lengths (below 1 m), which can generally be attacked directly with hand tools.

4.3. Fire severity and growth response

Tree mortality two years after the fire was higher for light intensity thinning as there were many small diameter trees left in the stand. Heat during prescribed burns could damage those trees with thinner barks and lower crowns, corresponding to suppressed trees or intermediate crown classes trees, which are the ones that are removed in traditional low thinning. In any case, the final density of the stand after two years, including tree mortality, was similar to other thinning treatments performed in similar *Pinus nigra* forest structures and followed silvicultural guidelines for the species (González et al., 1999; Beltrán et al., 2012).

A positive effect on diameter growth was observed in both heavy thinning units (lop and scatter or burn), which confirms that heavy thinning treatments are more effective for increasing the growth diameter of trees (González et al., 1999; Palahí and Grau, 2003) and that prescribed burns do not have a negative impact on the potential growth of dominant *Pinus nigra* trees (Valor et al., 2015).

4.4. Fuel management implications

The effectiveness of low thinning without slash management is unclear because immediately after the treatment the amount of dead fuel load increases. Simulation studies have shown that thinning without subsequent slash reduction is less effective than prescribed fire for reducing potential wildland fire behavior but more effective than no treatment (Kalabokidis and Omi, 1998; Fulé et al., 2002; Agee and Skinner, 2005; Stephens and Moghaddas, 2005). However, other simulation studies found thinning without a post-fire treatment less effective than their corresponding non-treated units (van Wagtendonk, 1996; Agee and Lolley, 2006). What we observed in this study was that when the resulting fuel from the thinning is lopped and scattered the arrangement and compactness of the slash on the surface greatly influences the fire behavior.

Table 7
Tree mortality, fire injury indicators and growth response 2 years after treatments (mean ± se). C, Control; TL, Light thinning and lop and scatter; TLB, Light thinning and burn; TH, Heavy thinning and lop and scatter; THB, Heavy thinning and burn.

Treatment	Mortality	Mean diameter of dead trees	Scorch height	Canopy length reduction	Canopy base height increase	Diameter growth
	(trees ha^{-1})	(cm)	(m)	(%)	(%)	(mm)
C	0	–	–	0	0	6.38 ± 2.48
TL	0	–	–	2.68	2.14	7.86 ± 2.58
TLB	414	10.18 ± 2.12	5.55	2.01	1.19	6.60 ± 2.64
TH	0	–	–	1.82	0.97	12.74 ± 4.32
THB	223	12.37 ± 2.74	6.16	7.34	6.11	13.52 ± 7.48

According to the results of our study we can state that thinning followed by fire is a good management alternative for *Pinus nigra* forests. Low thinning of light intensity keeps the canopy closed, thus allowing greater control of understory growth. Instead, heavy intensity thinning, with a greater canopy opening, is expected to develop more understory faster over time, and thus lose effectiveness.

The evaluation of the effectiveness of treatments in the medium term (5–10 years) is of overriding interest. Further research should focus on studying the evolution of the understory, the compactness of the slash, the variation in vertical discontinuity, and also the possible effects of prescribed burns on tree and vegetation regrowth. This, together with an economic assessment of the treatments, can provide land managers with tools for choosing the most appropriate fuel treatments to achieve their final objectives.

5. Conclusions

Regardless of the harshness of the meteorological scenario, treatments reduce fire intensity and result in a more homogeneous fire behavior response compared to no treatment. Our findings suggest that in a climate change context with drier and hotter meteorological scenarios, treatments that change either the fuel structure or decrease the fuel load facilitate adaptation to the changing weather conditions and improve the chances of survival. Investment into fuel management practices greatly assists adaptation to climate change and reduces its effects on fire behavior.

We suggest that fire behavior criteria (optimum dead fuel load, fuel bed depth, crown base height and crown bulk density) should be included in silvicultural treatment guidelines together with fire management and ecological principles. This would help in determining the most suitable treatment for each species and forest structure in each stage of their ecological succession.

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